Low-weight, Low-cost, Low-cycle Time, Replicated Glass Mirrors

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ITT has patented and continues to develop processes to fabricate low-cost borosilicate mirrors that can be used for both ground and space-based optical telescopes. Borosilicate glass is a commodity and is the material of choice for today's flat-panel televisions and monitors. Supply and demand has kept its cost low compared to mirror substrate materials typically found in telescopes. The current technology development is on the path to having the ability to deliver imaging quality optics of up to 1m (scalable to 2m) in diameter in three weeks. For those applications that can accommodate the material properties of borosilicate glasses, this technology has the potential to revolutionize ground and space-based astronomy. ITT Corporation has demonstrated finishing a planar, 0.6m borosilicate, optic to <100 nm-rms. This paper will provide an historical overview of the development in this area with an emphasis on recent technology developments to fabricate a 0.6m parabolic mirror under NASA Earth Science Technology Office (ESTO) grant #NNX09AD61G.

I. INTRODUCTION

Traditional lightweight glass mirrors that require precise surface figures to perform in systems that operate from the Ultraviolet (UV) to the Infrared (IR) are finished using conventional grinding and polishing techniques (including the more modern techniques of Ion Beam Figuring and Magneto-Rheological Fluid (MRF) polishing). Though most of these processes are deterministic, the inherent nature of the overall process is time consuming and relatively expensive. This is because a traditional glass optic needs to be processed multiple times after initial surface figure generation with finer abrasives and polishing compounds to remove subsurface damage. Large (>0.5m) aspheric lightweight optics can require months to years for fabrication. ITT has been developing new technologies that significantly reduce the cycle time to produce glass mirror-blanks and that reduce the cycle time to finish the mirror blanks into optical quality mirrors.

The end goal of the technology is to develop a set of processes that will yield lightweight ($<10 kg/m^2$) mirrors that are replicated without the need for conventional grinding and only a short duration polish to yield optics capable to work in diffraction limited visible and IR optical systems. Technologies have already been developed that reduce the cycle time in manufacturing mirror blanks from months to weeks in both Corning ULE® and various borosilicate glasses. ITT continues to develop processes and technologies that will enable the rapidly produced mirror blanks to be replicated to optical tolerances over a precision mandrel resulting in even further reductions in cycle time and cost.

The majority of development in glass mirror replication has utilized borosilicate glasses because they are inexpensive (flat panel display market), available in thin fire-polished sheets, and easier to work with than other glasses such as fused silica or Corning ULE®. One of the first of mirror borosilicate blanks, comprised of three layers of glass is shown in Fig. 1. The optic shown was fabricated with four pieces of glass for: 1) the front face sheet, 2) the back face sheet, 3) the outer diameter edge wall, and 4) the lightweight corrugated core. The lessons learned in developing manufacturing processes in borosilicate can be extended into other glasses. ITT has started to develop the processes and tooling required for fabricating ULE® corrugated mirror blanks, such as the one shown in Fig. 2. ITT has developed several different configurations of corrugated mirrors that have different numbers of glass layers. When referencing these different layers, the naming convention in this paper starts with the front reflective surface as being layer-1, with subsequent layers referred to with higher layer numbers (i.e. in the 5-layer mirrors discussed in the next section, the reflective surface is layer-1, and the back surface is layer-5).

II. FIRST GENERATION 5-LAYER CORRUGATED MIRRORS

ITT has used the lessons learned during early development of the corrugated mirror technology on smaller parts and has

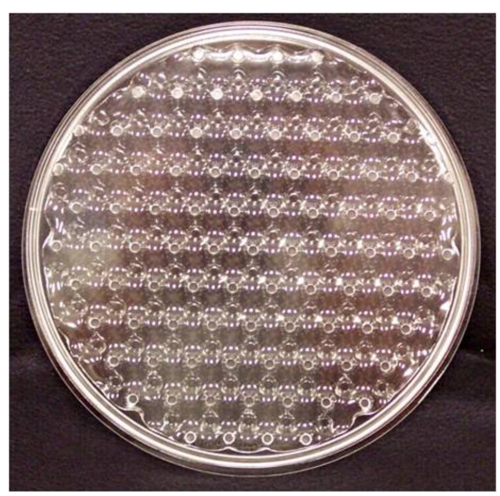

Fig. 1: Early borosilicate corrugated mirror blank prototype: 254 mm diameter, 3-layer, 1.1mm thick face sheets, and 6.35mm deep corrugation

Fig. 2. A ULE® 3-layer corrugated mirror blank

Fig. 4. ITT fabricated 5 first generation plano mirror blanks over several months using a single furnace. It takes about 1 week to produce a blank.

scaled up designs and tooling to enable the fabrication of parts that have an outer diameter of approximately 0.6m. The first 0.6m parts fabricated were plano (flat), do not have center-holes, and were comprised of five layers. The top three layers are fused as a sub-assembly and serve as the front face sheet. The sub-assembly is approximately 7mm high and has a micro-corrugation for its core (layer-2), to provide added stiffness to the front face sheet. The micro core was designed for minimal micro quilting ($\lambda/50$) and to minimize surface quilting that results from the large macro core (layer-4) which supports it. This added design feature results in a 5-layer optic which has significantly improved the structural efficiency compared to the early 3-layer prototypes. The 5-layer design enables the fabrication of lower areal density parts with better surface figure. Fig. 3 shows a sectioned 3-layer sub-assembly. To protect the macro core from contamination and to provide for a mounting surface, layer-5 is formed with an integral sidewall that is crimped to layers one and three during final assembly. In this first generation design, layer-2 and layer-4 perimeters were unsupported. This resulted in areas of point contact between layer-4 and layer-5. The potential impact of stress concentrating factors at the contact points was a topic of concern that was remedied in subsequent mirror designs.

ITT has fabricated all of the 0.6m corrugated blanks with a 2mm thick layer-1 front face sheet to allow for conventional grinding and polishing of the optic. Once replication processes are more mature, layer-1 will be fabricated with thinner glass, resulting in an areal density reduction of 2-3kg/m^2 yielding optics in the 8-9kg/m^2 range.

ITT fabricated several of these first generation plano parts (See Fig. 4) and turned some of them into assemblies by attaching mounts as shown in Fig. 5. Some of the demonstration parts and assemblies of unfinished mirrors were subject to acoustic and random vibration testing to advance the Technology Readiness Level (TRL). NASA Goddard. performed this testing with funds received through the NASA Innovative Partnerships Program. ITT polished one of the mounted mirror assemblies to a surface figure of 52nm-rms, bringing plano, borosilicate, corrugated optics to TRL 5. Fig. 5 shows the surface figure map of this mirror

III. SECOND GENERATION 5-LAYER CORRUGATED MIRRORS

The second generation corrugated optics that ITT developed advanced the previous technology in two ways. The first design change improved the layer-4 to layer-5 point contact issue. This was done by redesigning layer-4 with a continuous lip that could be crimped with layers 1, 3, and 5

Fig. 3. Section of 3-layer micro core used as the front face sheet for a 5-layer corrugated mirror design.

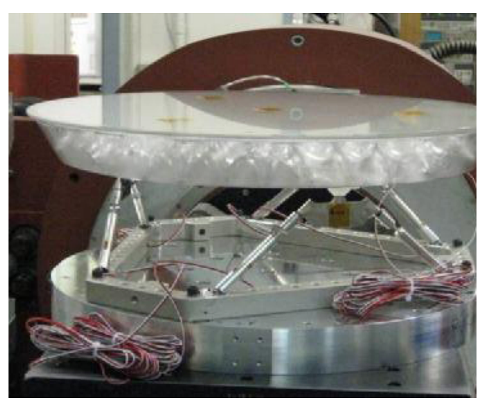

Fig. 5. A mounted first generation, 5-layer borosilicate mirror blank instrumented for vibration testing.

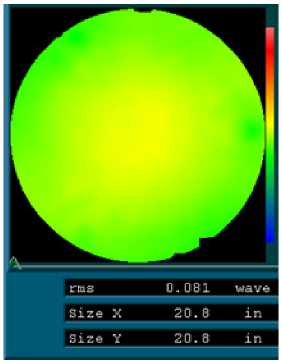

Fig. 6. Surface map of mounted plano corrugated optic is 52nm-rms over 90% of the 0.6m diameter physical aperture.

during final assembly. The redesigned layer-4 macro core is shown in Fig. 7. The second advancement was the initial development of a replication process for curved parts. A fully assembled 5-layer plano blank was formed against an f/2 sphere yielding near net-shaped parts. Unfortunately, due to budget constraints, none of the f/2 spheres were polished. However, the work accomplished during this technology development phase laid sufficient groundwork to enable development of 0.6m diameter parabolic mirrors with center-holes. The NASA ESTO funded the development of the third generation corrugated mirror technology.

IV. THIRD GENERATION 5-LAYER CORRUGATED OPTICS AND EARTH SCIENCE MISSIONS

The corrugated mirror is suitable for several active and passive Earth Science missions including ICESatII, DENDynI, ASCENDS, ACE, LIST, 3D Winds, and GACM. It also has applications in other sciences and telescopes. The “corrugated mirror” approach to telescopes offers multiple advantages:

• One mature architecture is an array of modest size mirrors which can achieve $3m^2$ of effective aperture where conventional approaches are limited to $1m^2$.

• An array of individual telescopes can be distributed on the platform in a variety of formats which often enable more receiver area to be deployed than could otherwise be accommodated.

• The telescope can be coupled to the detector via multimode optical fiber. This is a key advantage for applications where there are ‘radar antenna’ locations which are not suitable for an optical instrument, but which are suitable for a fiber coupled telescope. It also eliminates the need for relay optics and optical benches.

Fig.7. Second generation layer-4 macro core is more robust than the first generation concept.

• The low cost of this technology enables the use of multiple static telescopes as an alternative to a single large articulated telescope and the attendant challenges to the spacecraft.

• There are passive mirror missions which require large apertures, for which the deployable telescopes have been considered, but which remain too expensive.

• The recurring cost for identical mirrors is very low; a feat which current manufacturing techniques cannot achieve.

Under the Advanced Component Technology (ACT) grant awarded to ITT, processes have been developed to fabricate 0.6m diameter plano borosilicate mirror blanks with center-holes and then form them into f/1.95 parabolas over a 0.5m clear aperture. As with the previous generation optics, the mirror blanks generated under the grant funding all have 2mm thick front face sheets. During the ACT program, ITT fabricated a total of seven parabolic mirror blanks. The areal density of the optics is approximately $11kg/m^2$. All of these blanks matched the target radius of 1950mm to <0.2%. The best fit radius, averaged over the seven blanks was 1954.928 mm. This delta in radius can be accommodated by most telescope architectures. Additional empirical and analytical work should allow for a slight change in the spherical mandrel prescription yielding the target radius to even tighter tolerances if required.

ITT has polished one of the seven blanks and is currently polishing a second blank. The first parabolic blank was conventionally polished to 365 nm-rms (Fig. 8). This surface figure is well within the capture range of ITT’s deterministic ion figuring process. The part has gone through a single iteration of ion figuring. As of this writing, optical metrology has not yet been performed on the part. However, given the success in ion finishing the first generation plano part to a figure of 52nm-rms, we anticipate that the parabolic mirror could be finished to a comparable surface quality.

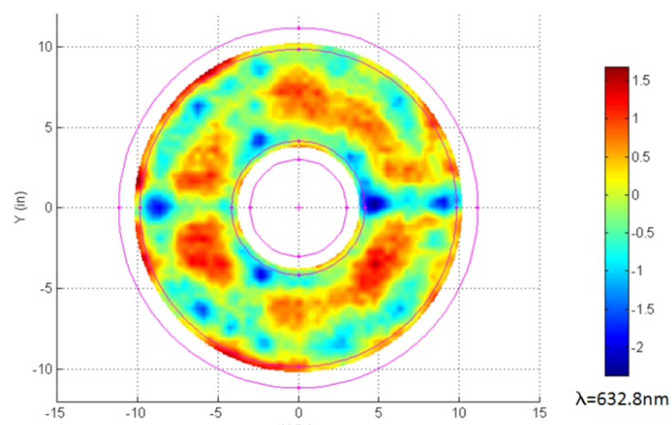

Fig. 8. ITT polished the first parabolic blank under the ESTO ACT funding to a surface figure of 365 nm-rms, prior to ion figuring

V. CONCLUSIONS AND NEXT STEPS

ITT continues to advance the state-of-the-art in fabricating low-weight, low-cost, low-cycle time borosilicate corrugated mirrors. The recent work performed indicates that mirror replication, which eliminates the relatively time consuming and costly grinding processes in turning a mirror blank into a finished polished mirror, are well within reach. Continued investment in the technology will allow for the manufacturing processes developed to be extended at a larger variety of materials. Furthermore, for borosilicate optics, glass manufactures are expected to continue to invest in glass fabrication technologies to support the flat panel display market yielding glass that is thinner and larger than what is currently on the market. This will enable the fabrication of lighter and larger optics. Currently, Schott produces a Borofloat glass at 0.7mm thickness that could be obtained in widths of > 2m.

ACKNOWLEDGMENT

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